HIGH-ENERGY HIGH-Q CAPACITOR BANKS DRIVING HIGH-CURRENT LONG-DURATION ARC DISCHARGES

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Abstract

High-energy capacitor banks have been constructed to investigate long-duration (100 μs to >10 ms) high-current wire-initiated arc discharges. In particular a megajoule bank which produces large currents with high voltage-reversal has been constructed. This capacitor bank is used in a high-Q circuit with a specially constructed low-loss, 1.7 mH inductor. The effects of low frequency and high-voltage reversal on these capacitors are described. Also, the effects of high-coulomb transfer on a high-action spark gap are presented. A spectroscopic observation system capable of measuring visible emission from these discharges has been constructed and is used to obtain electron number density and temperature measurements versus the discharge radius, as well as provide information on the time evolution of the discharge composition.

Introduction

High-current arc discharges are of interest for many pulsed-power applications. While the general principles of electrical conduction in arcs are known, the specific mechanisms that control initiation, conduction impedance, and sustainability are complicated and depend on the specific arc parameters. We characterize long-duration, damped-sinusoidal, wire-initiated arcs using variously sized capacitor banks, inductors and switches in a high-Q circuit to provide different currents for different time durations. Each of these components will be discussed in detail below. We intended to use capacitor banks ranging from 100 kilojoules up to 4 megajoules, but encountered difficulties with the capacitors while constructing a one-megajoule bank. Consequently, all the spectroscopy data taken to date use the 100 kJ bank. Analysis of the spectroscopic data permits measurement of plasma composition, electron density, and temperature versus radius, all with good temporal resolution. This information is used to characterize the arc.

Experimental Setup

Two high-energy capacitor banks have been constructed to investigate long-duration high-current wire-initiated arc discharges. In particular, a nominal one-megajoule bank which produces moderate currents with high voltage reversal has been constructed, and an upgrade to four megajoules is being fabricated. This capacitor bank forms part of a high-Q circuit with a specially constructed low-loss, 1.7 mH inductor. Also, a 100 kJ capacitor bank was constructed to obtain emission spectroscopy information to characterize the long-arc discharges. This 75 μF bank is in series with a commercially available 20 mH inductor to produce a long-duration discharge. The banks are switched using a commercially available high-action spark gap.

1 MJ Capacitor Bank

The one megajoule bank was to consist of 20 capacitors (206 μF each) in parallel, each storing a maximum of 50 kJ. The capacitors were to be connected in series with a commercial spark gap, a specially constructed 1.7 mH, 8.8 mΩ inductor and the arc load. The resulting discharge was designed to oscillate with a period of 17 ms and produce voltage reversals greater than 60%. Current and voltage waveforms of a typical discharge into a 1 m arc load is shown in figure 1. This section will discuss the performance of the 50 kJ capacitors under high voltage reversal, the inductor design and fabrication, and the spark-gap performance.

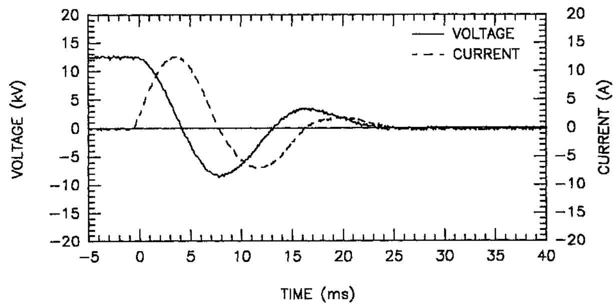

Figure 1. Capacitor voltage and current versus time with a 1 m wire-initiated arc.

Capacitors: The capacitors used in this experiment were the standard 50 kJ paper/foil Scyllac type and were procured from Aerovox Inc. Because of a high end-of-line failure rate (the capacitors failed dielectric hipot tests), the last shipment of capacitors was delivered almost one year after the contracted delivery date. Due to this delay, only 17 capacitors were pressed into service, bringing the bank energy and capacitance down to 850 kJ and 3.5 mF.

The capacitors are rated by Aerovox for a lifetime of 2000 shots at full voltage and 10% reversal. However, we purposefully subjected the capacitors to a normal duty of voltage reversals greater than 60%. Since damage from voltage reversal increases with the reversal and decreases with initial voltage, we performed two tests to establish a maximum operating voltage for the capacitors in our circuit. First, one capacitor (number 4184) was discharged into a 50 mH inductor five times from 10 kV, five times from 15 kV, and then tested to failure from 20 kV. This produced an underdamped capacitor voltage with a period of 20 ms, a decay time of 83 ms and a reversal of 90%. On the second shot from 20 kV the capacitor failed internally. Next, another capacitor was discharged 100 times into the same circuit from 15 kV without incident. Thus, the maximum operating voltage for the bank was conservatively set at 15 kV (recall that the capacitors were to be used in a 60% reversal circuit). Once the bank of 17 capacitors was assembled, two low-voltage (5 kV and 7.5 kV) check-out shots into a short were performed. These shots produced an underdamped capacitor voltage (16.7 ms period, 80 ms decay) with 90% reversal. Fourteen more shots were performed from initial voltages between 5 kV and 15 kV into a long wire-initiated arc, resulting in reversals between 60% and 70% and waveforms similar to the one in figure 1. During the charging cycle for the 17th shot, capacitor number 11522 failed at 8 kV, well below its rated voltage of 22 kV. The top welded seam of the capacitor was ripped open.

A post mortem of 11522 (see Fig. 2) revealed three interesting facts. First, there was no arc damage to the individual sections of the capacitor. The extended foil was torn away when the output bushing ripped free of its solder joint to the foil, but the paper (and foil) in the margin and the active region was completely unscathed by the arc. This indicates that the arc did not originate in the margin or active area of the dielectric, and so must have been confined to the head space above the capacitor sections. Second, a piece of insulation (≈.063 in. diameter by ≈.625 in. long) that appeared to have been stripped off a wire was found inside the capacitor near the head space. Figure 2 shows the location of this wire insulation during the post-mortem (it is likely that the insulation settled in this position while the castor oil was being pumped out of the capacitor). This object does not belong in a highly stressed capacitor. Third, small black deposits (≈0.125 in. diameter) were found in the margins of certain sections. About one

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 1993	**N/A**	**-**

4. TITLE AND SUBTITLE	
High-Energy High-Q Capacitor Banks Driving High-Current Long-Duration Arc Discharges	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Pulsed Power Systems and Technology Group (Code B20) Naval Surface Warfare Center Dahlgren, VA 22448-5000**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES

See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.

14. ABSTRACT

High-energy capacitor banks have been constructed to investigate long-duration (1 00 J.LS to > 10 ms) high-current wireinitiated arc discharges. In particular a megajoule bank which produces large currents with high voltage-reversal has been constructed. This capacitor bank is used in a high-Q circuit with a specially constructed low-loss, 1.7 mH inductor. The effects of low frequency and high-voltage reversal on these capacitors are described. Also, the effects of high-coulomb transfer on a highaction spark gap are presented. A spectroscopic observation system capable of measuring visible emission from these discharges has been constructed and is used to obtain electron number density and temperature measurements versus the discharge radius, as well as provide information on the time evolution of the discharge composition.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**4**	

dozen deposits were discovered scattered throughout the margins on two sections. These deposits were consistently located at wrinkles in the paper and foil on the end that was exposed to the head space arc. The cause of the black deposits is unclear.

A post-mortem of 4184 (the capacitor used to determine the operating range under high reversals) showed that the capacitor failed in the active area of the dielectric, about 2.5 inches below the margin (see figure 3). No black deposits were found in the sections. Since this capacitor was subjected to roughly the same number of shots as number 11522 (which was tested with less stressful voltages and reversals), and no deposits were found, it is unlikely that the deposits in capacitor 11522 were caused by the voltage reversals.

Following the failure of capacitor 11522, the remaining capacitors were tested individually to check for voltage holdoff ability (DC hipot). Capacitor 5006 showed a high leakage current and 5007 failed catastrophically at 22 kV, its rated voltage. All other testing was halted to avoid unnecessary damage. A post-mortem of 5007 showed that the capacitor failed in the margin of one section. Figure 4 shows the damaged area. It is impossible to determine the cause of this failure. Voltage-reversal damage and damage incurred from the fault of 11522 are two likely explanations.

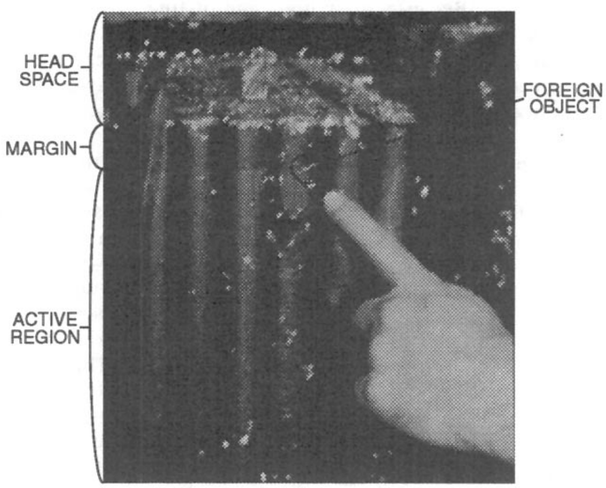

Figure 2. Photograph of a foreign object found inside the failed 50 kJ capacitor (side view of capacitor 11522 disassembled).

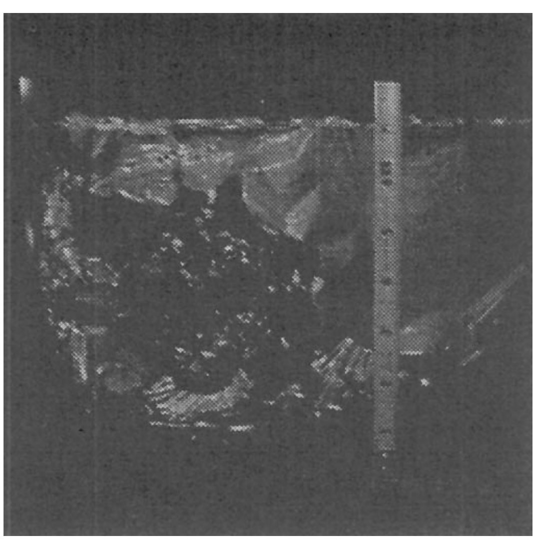

Figure 3. An example of an active area failure in a 50 kJ capacitor (side view of capacitor 4184).

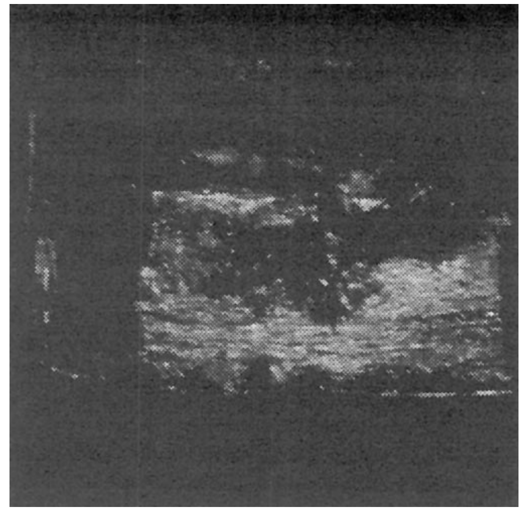

Figure 4. An example of a margin failure in a 50 kJ capacitor (top view of capacitor 5007).

For the upgrade to 4 MJ, we felt the difficulties with the standard 50 kJ capacitors indicated that we should acquire a lower energy-density capacitor. Thus, we contracted for 160 capacitors at 103 μF, 22 kV (25 kJ) each from NWL Capacitors. As part of the procurement, the manufacturer successfully demonstrated operation of their capacitor under two conditions: a 100 kA discharge with no reversal, and a 750 A discharge with a 17 ms period, 90 % reversal and a 105 ms decay. To weed out early failures, each capacitor is tested under the latter conditions as they arrive. All twenty-four capacitors received to date have been tested, with two failures. These units failed a hi-pot test subsequent to the high-reversal test. No post-mortem analysis has been performed.

Inductor: A high-Q 1.7 mH inductor was constructed for these banks. The inductor is designed for low-loss, high-voltage and modest-current applications. It consists of three sections connected in series (aiding). Each section is fabricated of 6.5 inch wide, 0.063 inch thick copper sheet wound to form a 14.75 inch ID, 20.3 inch OD, 6.5 inch tall coil with 32 turns. The inductance of each coil is ≈400 μH, and its resistance is ≈3.0 mΩ. Each turn is individually half-lap wrapped with 0.007 inch thick epoxy-impregnated B-stage insulating tape; curing the tape provides the turn-to-turn insulation and the mechanical strength needed to contain the magnetic forces. The three coils are stacked coaxially, separated by nylon plates 1.5 inches thick and interconnected via copper blocks soldered onto the coil ends. G-10 plates are used to sandwich the entire coil, and it is supported on ceramic insulators. The coil is designed to carry the maximum bank current of 60 kA, and to holdoff 250 kV. The assembled inductor is 1.7 mH, 8.8 mΩ, stands 24.5 inches tall and weighs ≈830 pounds.

Spark Gap: A Physics International spark gap, model ST-300, was used to trigger the bank on five of the seventeen shots. The switch is advertised to transfer 800 Coulombs in a single shot without damage. Due to the difficulties with the 1 MJ bank, we were only able to test the gap to 400 Coulombs in a single shot; the total charge transferred by the switch was ≈1000 C in five shots. The area damaged from each shot was quite large, although the total lost material was much less significant. The poco-graphite electrodes flaked off pieces 0.01 to 0.02 inches thick from areas of 0.09 to 0.15 square inches. No triggering or holdoff problems resulted from the erosion. The aluminum housing that surrounds the gap area is also the return conductor. Several arc spots were located on the housing, with heavy erosion of the metal. This could have been caused by the long pulse length (underdamped, 17 ms period, 80 ms decay for the highest coulomb shots) allowing the arc to migrate to the conducting walls. The switch was triggered using UV illuminators supplied with the gap, which could

have enhanced the migration by causing the arc to form near the edges of the electrodes. The capacitors in the 1 MJ bank began failing before switch performance could be investigated further. Future tests using the 4 MJ bank will examine the survival of this switch during charge transfers well over 1000 C per shot (possibly as high as 4000 C per shot), with a zero-voltage triggering scheme used to break down the spark gap independently of any other applied voltage (see figure 5), that should eliminate any bias for the initiation point due to the UV illuminators.

100 kJ Capacitor Bank:

The 75 μF capacitor bank (50 kV maximum charging voltage) is in series with a 20 mH inductor and a high-action spark gap with the wire-initiated discharge as the load as shown in figure 5. Typical current and voltage waveforms of the discharge are also shown for a 20 kV charging voltage. The resulting discharge was designed to oscillate with a period of 8 ms. A fast zero-voltage triggering circuit was used to trigger the high-action spark gap and drive the wire into a low-impedance plasma, initiating the discharge. The duration of the capacitor-bank-driven discharges is 10's of milliseconds while the duration of the zero-voltage triggering circuit is a few 10's of microseconds. This circuit can drive currents up to 3 kA through the wire-initiated discharges. A 20 μs, 50 Ω pulse forming network (PFN) was also used to simulate the fast wire-initiation characteristics of the discharge for spectroscopic observation.

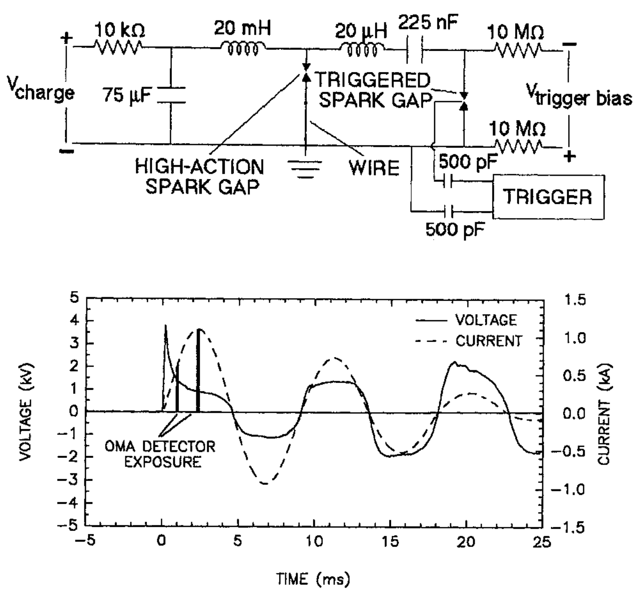

Figure 5. The experimental setup of the 75 μF capacitor bank circuit with the corresponding discharge voltage and current waveforms for a charging voltage of 20 kV.

Emission Spectroscopy System:

The emission spectroscopy setup consists of a coherent fiber-optic ribbon, a 0.6 m spectrometer and an EG&G optical multichannel analyzer (OMA). The light from the discharge is focused onto the fiber-optic cable and is guided to the input slit of the spectrometer where it is spread into a spectrum and recorded by the two dimensional OMA silicon-diode array. The spectral data is then stored in the computer for analysis. Single-shot three-dimensional information (wavelength versus chord-integrated intensity versus radius) can be obtained for any time during the discharge with 100 ns to 1 ms detector gate times. This spectroscopy setup was constructed to obtain discharge parameter measurements which are used to verify an on-going modeling effort [1].

Spectroscopy Results

Line of sight (i.e. chord) integrated spectra have been gathered from aluminum (1 m length and 40 μm diameter) and copper (0.2 m length and 16 μm diameter) wire-initiated discharges using the 100 kJ circuit discussed above. Figure 6 illustrates the radial structure of the discharge. Note that the light that ultimately reaches the spectrometer along the line of sight passes through the entire composition and temperature distribution; thus, the observed spectrum contains the influences of emission and absorption along the entire chord. The two neutral aluminum lines 3944 Å and 3961 Å are very bright where temperature and neutral density are large. However, this light passes through cooler, more absorbing regions as it propagates out of the discharge towards the spectrometer creating what is called a self-reversed spectrum (see figure 7). Therefore, it is intuitive that these self-reversed lines are sensitive to the plasma properties along the whole chord. The self-reversal of these two lines was used to obtain temperature (T) and electron number density (n_e) versus radius for the wire initiated discharge. Also, the ratio of a spectral line intensity pair (ratio of areas under the spectral profiles) gave an independent measurement of temperature while the Stark widths of spectral line profiles gave independent measurements of electron number density. All of these spectroscopic techniques gave a consistent picture for T and n_e in the discharge.

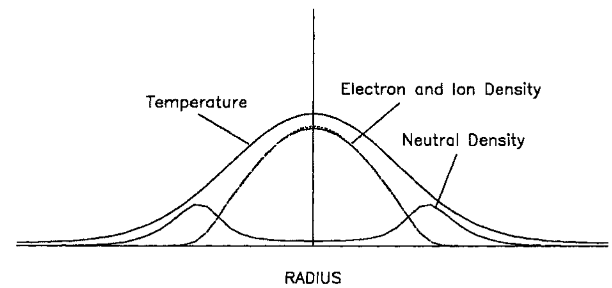

Figure 6. A representative illustration of the temperature, electron number density and neutral number density versus radius of the discharge.

The chord-integrated spectral output of the self-reversed aluminum lines for several chords transverse to the wire-initiated discharge are shown in figure 7. The distance of the chord from the discharge center is called the chord parameter. Analysis of the lines produce T and n_e versus radius for different times during the discharge as shown in figure 8. The discharge was initiated within a few 10's of microseconds using the fast triggering circuit. To simulate this, the 50 Ω PFN charged to 50 kV was used to obtain spectra at 10 μs into the 1 kA peak discharge. The discharge radius was approximately 0.3 cm, the peak temperature was approximately 1.8 eV, and the peak electron number density was 10^{18} cm^{-3}. Using the 75 μF capacitor bank charged to 20 kV and the 20 mH inductor, spectra were also obtained later in time. One millisecond into the discharge the radius was approximately 1.5 cm with a peak temperature of 2 eV and an electron number density of approximately $2x10^{17}$ cm^{-3}. Two milliseconds into the discharge (at peak current) the radius was slightly larger and T and n_e did not change noticeably. Also, Stark broadening measurements were made using a singly-ionized aluminum line at 3587 Å and a neutral aluminum line at 6695 Å [2,3]. The 3587 Å line gave $n_e = 2x10^{17}$ cm^{-3} and the 6695 Å line gave $n_e = 5x10^{16}$ cm^{-3}. These number densities and their spatial structure were consistent with the analysis of the self-reversed lines. These results quantify the expected initial hot dense plasma expansion to large diameters with time as the density and temperature are reduced. Also found from the spectroscopic measurements is that the initiating wire material was diffusing out of the discharge. Spectroscopic observation of a molecular nitrogen band confirmed that air is replacing the initial wire material within several milliseconds.

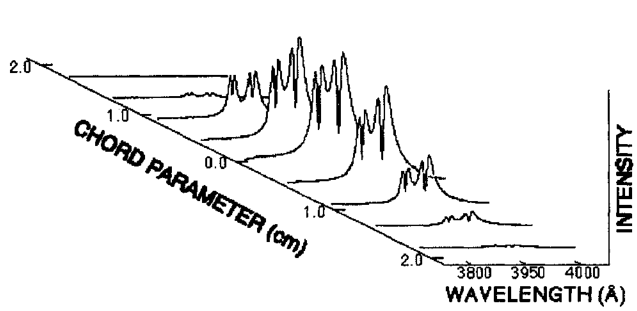

Figure 7. The chord-integrated intensity versus chord parameter for an aluminum discharge of the self-reversed aluminum lines at 3944 Å and 3961 Å.

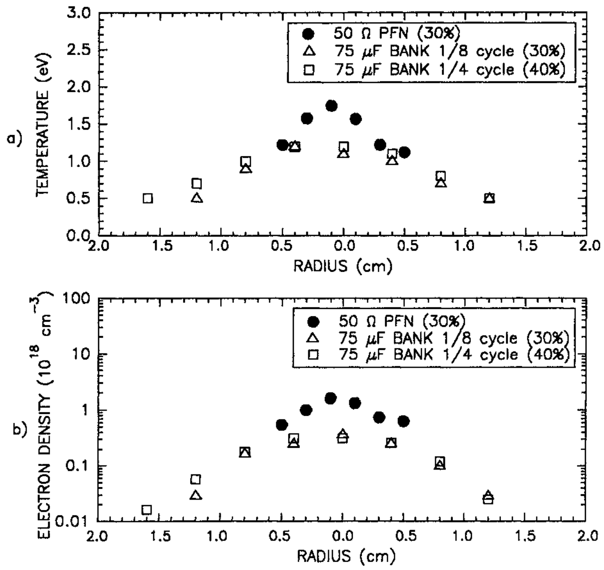

Figure 8. The results of the analysis of the self-reversed aluminum lines where a) is the temperature versus radius and b) is the electron number density versus radius for various times during the discharge. The value in parenthesis is the uncertainty associated with the measurement.

The chord-integrated spectral output of two neutral copper lines at 5105 Å and 5153 Å versus radius were also obtained. Since these lines were not self-reversed, analysis using the ratio of the integrated intensities and Stark broadening of the lines produced T and n_e versus radius for different times during the discharge as shown in figure 9. This analysis provides less spatial information than the self-reversed case since the cooler more absorbing regions of the discharge do not significantly influence the copper emission spectrum. In these discharges, the center of the discharge is highly ionized (devoid of neutral copper) so that the actual peak temperatures and number densities cannot be measured. Again, the discharge was initiated within a few 10's of μs and the PFN circuit was used to obtain spectra at these early times in the discharge where radius is approximately 0.3 cm, the largest temperature is approximately 1.9 eV, and the largest electron number density is $1\text{x}10^{18}$ cm^{-3}. Later in time during the discharge (≈1 ms), the radius is approximately 1.5 cm with a temperature of 1.4 eV and electron number densities of approximately $1\text{x}10^{17}$ cm^{-3}. However, at 2 ms into the discharge observed T and n_e are smaller. This is an indication that the neutral copper is being forced out to a larger radius (diffusion out of the discharge). Peak (center of the discharge) T and n_e are presumed to be higher since the neutral copper emission is produced in the cool, outer parts of the discharge.

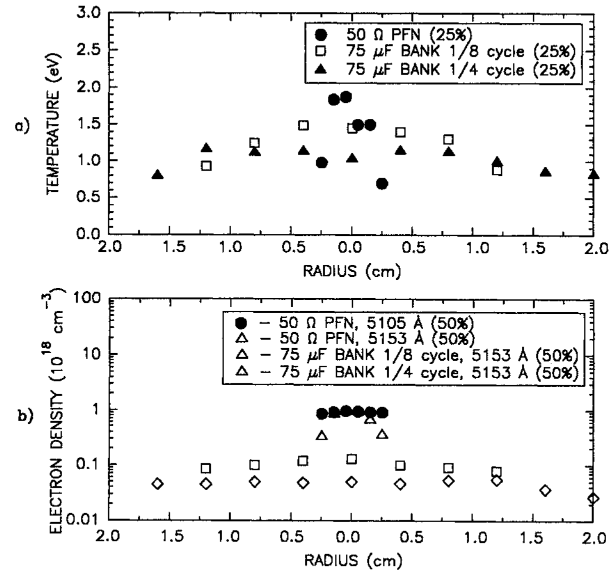

Figure 9. The results of the analysis of the ratio of the integrated line intensities and Stark broadening of the copper lines where a) is the temperature versus radius and b) is the electron number density versus radius for various times during the discharge. The value in parenthesis are the uncertainty associated with the measurement.

A comparison between the aluminum and copper wire-initiated discharge indicates that T and n_e are slightly higher in copper (probably due to the higher ionization potential of copper). Also, self-reversed lines provide more information about the radial discharge structure than non self-reversed lines. Several milliseconds after initiation, the self-reversal of the aluminum lines diminishes as the initial wire material leaves the discharge. Thus, the self-reversed analysis technique produces less certain density and temperature profiles. In the future, a spatial inversion technique will be developed to obtain discharge plasma properties later in time.

Summary:

High-energy capacitor banks have been constructed to drive wire-initiated discharges with durations of 10's of milliseconds. The high-energy bank was operated up to 15 kA with a ringing period of 17 ms. Difficulty with the construction of a 1 MJ bank using 50 kJ capacitors and information relating to capacitor failures by post-mortem observations were discussed. A lower-energy capacitor bank was operated at 1 kA peak and emission spectroscopy was used to measure the radial properties of T and n_e for long wire-initiated discharges. Copper and aluminum wire-initiated discharges were observed from the early stages of discharge initiation out to a few milliseconds. This information was used to experimentally verify a modeling effort.

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